Evaluation of Refractivity Profiles from CHAMP and SAC-C GPS Radio Occultation

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The Global Positioning System enables positioning in 3 dimensions about the Earth. The signals sent by twenty-four satellites travel through our atmosphere down to the small receivers used by the civilian community and the military. These signals are radio waves; their travel path in the atmosphere is dependent upon varying meteorological conditions.

A small GPS receiver was launched in space with the GPS/Meteorology experiment (GPS-MET) in 1995. For the first time, it became possible to perform a significant number of radio occultations around the Earth: from the standpoint of the receiver, the source - one of the 24 GPS satellites - would rise or set around the other side of the Earth. When the source would disappear, the receiver would progressively lose the signals. The delay induced by the atmosphere would then be inferred by measuring accurately the time delay between the emission and the reception of the signal.

In 2000, two second-generation GPS receivers were launched on-board the GeoForschungsZentrum's Challenging Mini-satellite Payload for Geophysical Research and Application (CHAMP, US-Germany) and the Comision Nacional de Actividades Especiales' Satelite de Aplicaciones Cientificas-C (SAC-C, US-Argentina). These second-generation "Blackjack" receivers have the ability to sense the lower troposphere closer to the surface than the proof-of-concept GPS/MET experiment. Since their launch, CHAMP and SAC-C have collected thousands of GPS radio occultations, representing a wealth of measurements available for data assimilation in Numerical Weather Prediction models.

In order to evaluate the data derived by the Jet Propulsion Laboratory from the raw radio occultation measurements of CHAMP and SAC-C, we use 6-hour forecasts produced by the Data Assimilation Office Finite Volume Data Assimilation System as an independent state of the atmosphere. We compare CHAMP and SAC-C refractivity retrievals with refractivity calculated from the forecast, i.e. global fields of temperature, water vapor content and humidity. We show statistics of the differences as well as histograms of the differences. Over one year of comparison, the statistics suggest a seasonal cycle in numerical forecast errors and/or processing errors (namely diffraction effects). This cycle appears stronger in the Northern hemisphere than in the Southern hemisphere.

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Summary. The GeoForschungsZentrum's Challenging Minisatellite Payload for Geophysical Research and Application (CHAMP, Germany-US) and the Comision Nacional de Actividades Especiales' Satelite de Aplicaciones Cientificas-C (SAC-C, Argentina-US) missions are the first missions to carry a second-generation Blackjack Global Positioning System (GPS) receiver. One of the new features of this receiver is its ability to sense the lower troposphere closer to the surface than the proof-of-concept GPS Meteorology experiment (GPS/MET). Since their launch, CHAMP and SAC-C have collected thousands of GPS radio occultations, representing a wealth of measurements available for data assimilation and Numerical Weather Prediction (NWP). In order to evaluate the refractivity data derived by the Jet Propulsion Laboratory (JPL) from raw radio occultation measurements, we use Data Assimilation Office (DAO) 6-hour forecasts as an independent state of the atmosphere. We compare CHAMP and SAC-C refractivity (processed by JPL) with refractivity calculated from the DAO global fields of temperature, water vapor content and humidity. We show statistics of the differences as well as histograms of the differences.

Key words: Radio-occultation - Refractivity - Skewness - Seasonal cycle

1 Introduction

The CHAMP and SAC-C missions have each collected more than 30,000 GPS radio occultations since May 2001 (July 2001, respectively). Theoretical studies [HE00] as well as studies based on GPS/MET data [PJK02] have suggested that GPS radio occultation data could have a potential impact on data assimilation applied to Numerical Weather Prediction (NWP) and/or climate

studies. With the wealth of GPS radio occultation data now available, the
NWP community is now given an amount of observations which compete in
number with other observing systems (e.g. radiosondes) with, for example, the
advantage that radio occultation observations collected by a high-inclination
Low-Earth Orbiter (LEO) are distributed more evenly on our planet.

In the present paper, we compare DAO 6-hour forecasts with CHAMP and
SAC-C refractivity, for a total of ~54,000 occultations. We also investigate
the distribution of the differences in terms of histograms to potentially verify
the usual assumptions used in variational retrievals and data assimilation
(Gaussian unbiased errors).

2 Methodology

In order to evaluate the refractivity derived from CHAMP and SAC-C, we
investigate time, latitude and altitude dependence of the differences between
DAO 6-hour forecasts and refractivity derived from radio occultation. We
focus here on 6-hour forecasts because our interest is future assimilation of re-
fractivity into latest available 6-hour forecasts. All the refractivity differences
are DAO forecasts minus (derived from radio occultation) (or "observed"), ex-
pressed in percent of observed refractivity, in order to account for the fact that
refractivity decays exponentially with altitude and spans about two orders of
magnitude between the surface and 30km altitude.

2.1 Refractivity Derived from DAO Forecasts

We ran the DAO Finite Volume Data Assimilation System between April 2001
and April 2002 with a horizontal resolution of 2×2.5degrees (lat/lon) and
55 levels between the surface and 0.01hPa. Conventional observations (in-
cluding radiosondes) as well as (A)TOVS brightness temperature and SSM/I
precipitable water were assimilated. No GPS radio occultation observations
were assimilated in this run. We derived local refractivity at the tangent point
latitude/longitude/altitude reported in each occultation by applying the for-
mula derived by Smith and Weintraub [SW53]. We did not perform any hori-
zontal averaging to account for the effects of horizontal refractivity gradients.

2.2 Refractivity Derived from CHAMP and SAC-C

We used the refractivity data derived by JPL, available through an anony-
mous FTP website. Details of the geometrical optics processing employed to
process the raw radio occultation measurements can be found in the literature
[HA02]. All occultations presenting more than 20% difference in refractivity
with respect to NCEP analyses were rejected by the data producers. We did
not apply any further quality control to the dataset. Table 1 shows the number
of occultations used in our study.

Table 1. Number of radio occultations.

	May01	Jun01	Jul01	Aug01	Sep01	Oct01	Nov01	Dec01	Jan02	Feb02	Mar02	Apr02
CHAMP	2295	3284	2352	1157	1715	2717	2666	1995	3245	2698	3785	2175
SAC-C	-	-	824	3249	3994	2835	2666	2339	3183	-	3467	1769

2.3 Origins of the Refractivity Differences

The refractivity differences we are looking at in the present paper arise from three error types: representativeness, observation, and forecast errors. The first errors include limitations in our observation operator (assumes local refractivity and does not account for horizontal gradients). The term 'observation errors' covers "GPS radio occultation"-related issues, many of which are discussed by other authors in the present volume (e.g. limitations of the geometrical optics processing, hardware and software tracking of the occultations etc.). Eventually, forecast errors represent a motivation for assimilating GPS radio occultation data in NWP.

3 Mean and Standard Deviation of the Differences: Large-Scale Space and Time Variations

It is primordial for the purposes of data assimilation to use adequate errors in order to ensure adequate weighting of the observations versus other sources of information (i.e. numerical forecast, other observations). These errors are usually modeled as Gaussian errors in data assimilation systems, thus requiring *a priori* knowledge of the mean departure (bias) as well as the standard deviation.

We investigate first the spatial variations of the differences at a given time (January 2002, entire month). Figure 1a shows the bias for the CHAMP minus DAO refractivity. This bias has already been reported by several authors [e.g. [RAE97]]. Its origins remain unclear. The magnitude of the bias decreases with altitude and is more important in the lower atmosphere, where water vapor is more abundant. We checked that the regions of higher bias move with latitude and seasons. Figure 1b is the same plot but for SAC-C refractivity. It is reassuring to notice very similar patterns, except for a small -0.5% bias in the Tropics between 7 and 20 km altitude.

Figure 1c shows zonal averages for the standard deviation of the differences. Those are larger in the lower layers where horizontal gradients play a larger role. The numbers agree with the SAC-C results shown in Figure 1d.

Figure 2a shows the variations in the standard deviations throughout one year (from May 2001 until April 2002) for CHAMP, at 5.5km altitude. For a set latitude in the Northern hemisphere (45°N for example), a seasonal cycle can be seen: larger standard deviations occur in July. This cycle appears
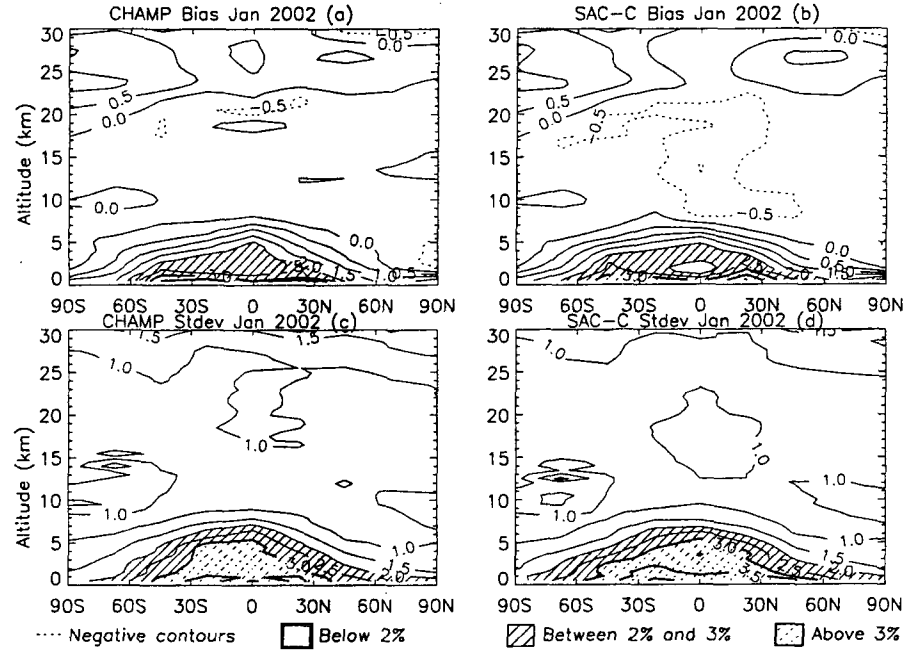
Fig. 1. Zonal averages of bias and standard deviation of the differences between CHAMP (SAC-C) and DAO 6-hour forecasts refractivity. Contour every 0.5%. See text for details.

smaller in the Southern hemisphere but the idea is similar. Larger standard deviations are observed in the summer hemisphere. Figure 2b shows similar results for SAC-C (note: no data for May and June 2001, and missing data for February 2002). Figure 2c is for a lower altitude (3.5km), where more humidity is present. Humidity may play a role in the refractivity differences through the three sources of errors. Consequently, it is not possible to sort out the origin of the seasonal cycle shown here. The seasonal cycle appears definitely stronger in the Northern hemisphere than in the South. These conclusions are reinforced by looking at Figure 2d (for SAC-C), as well as Figures 2e and 2f (2.5 km altitude).

4 Histograms of the Refractivity Differences

As stated earlier, assimilation methods usually assume Gaussian errors. We attempt to verify this assumption by inspection of histograms of the refractivity differences.

In order to account for the fact that polar regions cover a smaller area than tropical regions, we included an area-weighting factor in the calculations. It is to be noted that this did not alter fundamentally the results. Figure 3a shows
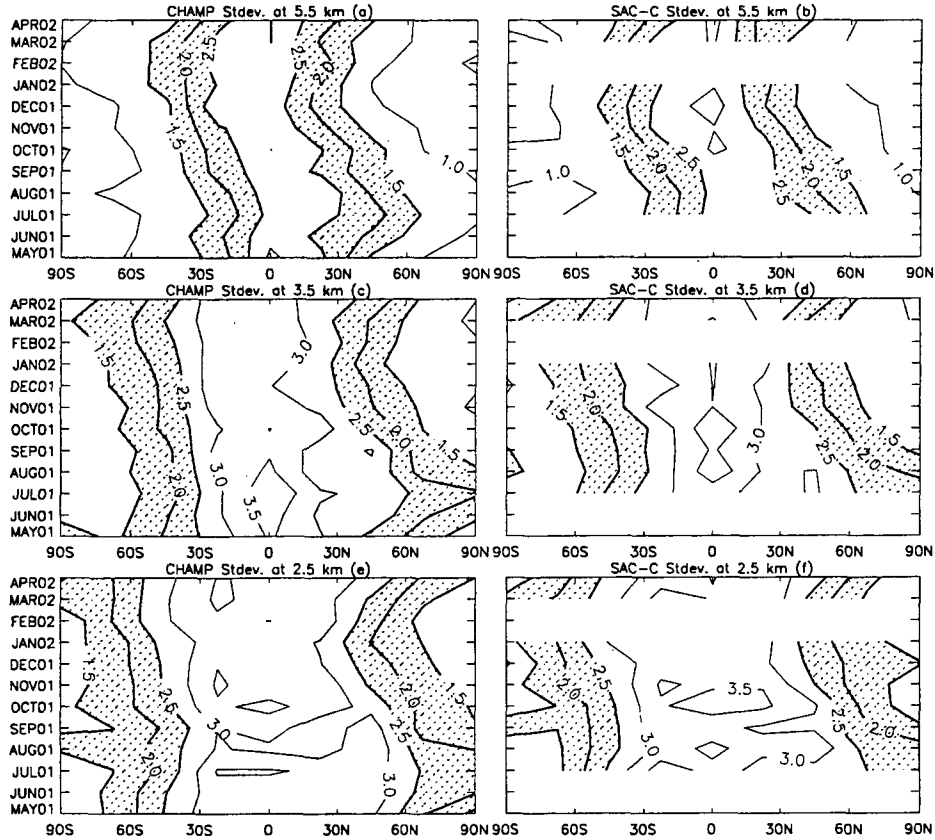
Fig. 2. Time evolution of the quantities shown in Figure 1 for several altitudes (2.5km, 3.5km, and 5.5km, standard deviations only). Shaded area: standard deviation between 1.5% and 2.5%.

the repartition of refractivity differences (DAO minus CHAMP) for all occultations between May 2001 and April 2002, at 2 km altitude. The histogram in Figure 3a exhibits a skewed shape. The mode of the distribution is at zero, which indicates that the maximum likelihood is encountered for differences of zero. However, events with a positive differences are more common than events with a negative difference, thus leading to a skewness, and then a bias (1.3%) in the distribution. The Gaussian fit, also plotted in Figure 3a, shows the positive bias which results from the skews distribution.

For an altitude of 12 km, Figure 3b shows that the skewness has disappeared. The bias is relatively small (less than 0.1%). However, a departure from the Gaussian shape is apparent for zero differences: such events are more frequent in reality than modeled by a Gaussian curve.

We investigated the latitudinal dependence of the skewness illustrated in Figure 3a. No clear conclusion could be drawn. It remains that the skewness

is limited to lower portions of the atmosphere. Although-not shown here, we obtained very similar results by looking at histograms of DAO minus SAC-C refractivity.
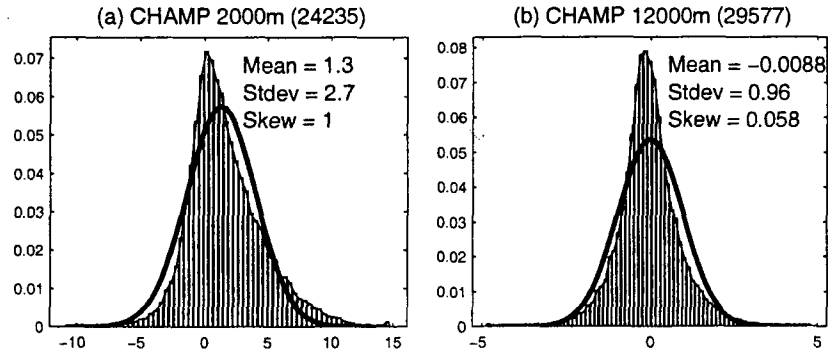

Fig. 3. Histograms of the refractivity differences for CHAMP, at two different altitudes, (May 2001-April 2002, all latitudes). Thick line is Gaussian fit. Number of comparisons in parentheses.

5 Conclusions and Future Directions

This study compares about 30,000 CHAMP and 24,000 SAC-C refractivity profiles with DAO 6-hour forecasts. The results obtained in this study will be used to refine error characteristics in order to perform one-dimensional variational analyses of the refractivity profiles derived by radio occultation. It seems that the refractivity differences do not vary with much intensity over time, although a seasonal cycle in the differences is observed for mid-latitudes in both hemispheres (apparently stronger in the Northern hemisphere than in the South). The refractivity differences show fairly constant means and standard deviations between 12 and 28 km altitude.

The histograms of refractivity differences present skewed distributions. It is not clear for now if this is due to the processing technique, insufficient modeling in our observation operator, or if it is a feature of the DAO model errors. In any case, this skewness seems to be related with the "refractivity bias". It deserves more attention.

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